

F. Fernández, D. R. Entem, P. G. Ortega, J. Segovia

From J/ψ to LHCb pentaquark

Few-body issues on the hadron spectrum

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Abstract The original charmonium two-body problem, like the $c\bar{c}$ structure of the J/ψ meson, has become more involved in the last few years with the discovery of new resonances such as the tentative molecular state $X(3872)$ or the possible pentaquark one $P_c(4380)^+$. We discuss herein how these exotic states (and others) can be described in a unified way adding higher Fock state components to the naive quark model picture. In particular, we present our theoretical results on the pentaquark states $P_c(4380)^+$ and $P_c(4450)^+$, and on the new charmonium-like resonances $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$ that have been reported in 2016 by the LHCb Collaboration.

Keywords Potential models · Charmed hadrons · Exotic hadrons

1 Introduction

Charmonium history began in 1974 with the discovery of the so-called J/ψ particle. Soon after that, it was realized that J/ψ could be described as a bound state of a charm quark and a charm antiquark, namely as a two-body problem. Moreover, owing to the large mass of the charm quark, the system could be considered in a first place by its nonrelativistic nature and thus solving the Schrödinger equation with a well motivated QCD potential was a successful approach to the problem at hand.

The discovery in 2003 of the $X(3872)$ resonance made evident that the naive quark model picture is not enough to describe its properties. For instance, the large mass of the $X(3872)$ and its zero isospin value point out that it is made by charm quarks; on the other hand, the isospin violating decay $X(3872) \rightarrow J/\psi \rho$ makes the $X(3872)$ difficult to accommodate as charm-anticharm state. However, the decay mentioned above can be naturally explained in a picture in which the $X(3872)$ is understood as a DD^* bound state, namely a four-quark bound-state problem.

During the last decade, experimental observations have revealed the existence of a large number of unexpected states such as the $X(3872)$, culminating recently with the observation by the LHCb

F. Fernández
Grupo de Física Nuclear and Instituto Universitario de Física Fundamental y Matemáticas (IUFFyM),
Universidad de Salamanca, E-37008 Salamanca, Spain
E-mail: fdz@usal.es

D. R. Entem
Grupo de Física Nuclear and Instituto Universitario de Física Fundamental y Matemáticas (IUFFyM),
Universidad de Salamanca, E-37008 Salamanca, Spain
E-mail: entem@usal.es

P. G. Ortega
Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia, ES-46071 Valencia, Spain
E-mail: pgortega@ific.uv.es

J. Segovia
Physik-Department, Technische Universität München, James-Frank-Str. 1, 85748 Garching, Germany
E-mail: jorge.segovia@tum.de

Table 1 Masses and width of the different pentaquark states

Molecule	J^P	I	M (MeV)	$\Gamma(J/\psi p)$ (MeV)	$\Gamma(\bar{D}^* \Lambda_c)$ (MeV)
$\bar{D} \Sigma_c^*$	$\frac{3}{2}^-$	$\frac{1}{2}$	4385.0	10.0	14.7
$\bar{D}^* \Sigma_c$	$\frac{1}{2}^-$	$\frac{1}{2}$	4458.9	5.3	63.6
$\bar{D}^* \Sigma_c$	$\frac{3}{2}^-$	$\frac{1}{2}$	4461.3	0.8	21.2
$\bar{D}^* \Sigma_c$	$\frac{3}{2}^+$	$\frac{1}{2}$	4462.7	0.2	6.3

collaboration in 2015 of two charmonium pentaquark states $P_c(4380)^+$ and $P_c(4450)^+$ [1]. Therefore, we have gone from a two-body problem to a five-body problem passing through a four-body one in less than 15 years.

In this proceedings contribution we present a unified description of all these states within the framework of a constituent model of quarks. The model has already been applied to two- and four-quark structures and is now being applied to the study of five-quark states. In addition, we discuss herein a set of four resonances recently measured in the LHCb [2]: $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$, which have been considered as new multiquark states [3] but in our scheme most of them appear as simple quark-antiquark structures.

2 The constituent quark model

Our constituent quark model (CQM) is based on the assumption that the light massless light quark acquires a dynamical, momentum dependent mass namely the constituent quark mass as a consequence of the dynamical chiral symmetry breaking of the QCD Lagrangian at some momentum scale. This constituent quark mass is frozen at low momenta at a value around 300 MeV and explains the 98% of the mass of the proton. The simplest Lagrangian which mimics this situation must contain chiral fields to compensate the constituent mass term. These chiral fields induce boson exchanges between quarks. In the heavy quark sector, chiral symmetry is explicitly broken and we do not need additional fields. However, the chiral fields introduced above provide a natural way to incorporate one-pion (OPE) interactions in the molecular (four-quark) dynamics. Higher pion exchanges than OPE are effectively included by scalar boson exchanges.

Besides the dynamically broken chiral symmetry, the other two main properties of QCD that are incorporated in our quark model are confinement and asymptotic freedom. To mimic such features we use a linear screened confining potential and a perturbative one-gluon exchange interaction. The detailed explanation and parametrization of all these interactions can be found in Ref. [4], updated in Ref. [5].

To obtain the solutions in the two-body case, we solve the Schrödinger equation using the Gaussian Expansion method [6] whereas the four and five-body problem are solved using the Resonating Group Method [7]. Two-quark and multiquark configurations are coupled using the 3P_0 method [8]. Details of the calculations are given in Refs. [9; 10]

3 The $P_c(4380)^+$ and $P_c(4450)^+$ resonances

We consider the $\bar{D} \Sigma_c^*$ and $\bar{D}^* \Sigma_c$ thresholds which are the only ones close to the mass of the $P_c(4380)^+$ and $P_c(4450)^+$ resonances and also where a sizable residual interaction mainly due to pion exchanges can be expected.

One can see in Table 1 that in the mass region of the $P_c(4380)^+$ we obtain a $\bar{D} \Sigma_c^*$ bound state with $J^P = \frac{3}{2}^-$. Its mass is very close to the experimental one and should, in principle, be identified with the observed $P_c(4380)^+$ structure.

Referring to the channel $\bar{D}^* \Sigma_c$, we find three almost degenerated states with a mass around 4460 MeV that makes them natural candidates for the $P_c(4450)^+$ resonance. The total spin and parity of these states are $J^P = \frac{1}{2}^-$, $\frac{3}{2}^-$ and $\frac{3}{2}^+$. Their degeneration may be the origin of the uncertainty in the experimental determination of the total spin and parity for the $P_c(4450)^+$ resonance.

It is remarkable that the three bound states predicted by our model decay into $\bar{D}^* \Lambda_c$ final state with a partial decay width which is generally equal to or larger than the width corresponding to the $J/\psi p$ decay channel. This suggests that the $\bar{D}^* \Lambda_c$ final state is a suitable decay channel for studying

Table 2 Naive quark-antiquark spectrum in the region of interest of the LHCb [2?] for the 0^{++} and 1^{++} channels.

State	J^{PC}	nL	Theory (MeV)	Experiment (MeV)
χ_{c0}	0^{++}	$3P$	4241.7	—
		$4P$	4497.2	$4506 \pm 11^{+12}_{-15}$
		$5P$	4697.6	$4704 \pm 10^{+14}_{-24}$
χ_{c1}	1^{++}	$3P$	4271.5	4273.3 ± 8.3
		$4P$	4520.8	—
		$5P$	4716.4	—

Table 3 Mass, total width (in MeV), and $c\bar{c}$ component probabilities (in %) for the $X(4274)$ meson, obtained from the coupled channel calculation described in the text

Mass	Width	$\mathcal{P}_{c\bar{c}}$	$\mathcal{P}_{D_s D_s^*}$	$\mathcal{P}_{D_s^* D_s^*}$	$\mathcal{P}_{J/\psi\phi}$
4242.4	25.9	48.7	43.5	5.0	2.7

Table 4 Probabilities, in %, of nP $c\bar{c}$ components in the total wave function of the $X(4274)$ meson.

Mass (MeV)	$\mathcal{P}_{c\bar{c}}$	\mathcal{P}_{1P}	\mathcal{P}_{2P}	\mathcal{P}_{3P}	\mathcal{P}_{4P}	$\mathcal{P}_{(n>4)P}$
4242.4	48.7	0.000	0.370	99.037	0.488	0.105

the properties of these resonances. In particular, the width of the predicted $\bar{D}^* \Sigma_c$ resonance with $J^P = \frac{1}{2}^-$ is twelve times larger through the $\bar{D}^* \Lambda_c$ channel than through the $J/\psi p$ channel, making this decay an important check of our prediction.

Concerning the parity of the states, a molecular scenario is not the most convenient to obtain positive parity states because, being the $\bar{D}^{(*)}$ mesons and the $\Sigma_c^{(*)}$ baryons of opposite parity, the relative angular momentum should be at least $L = 1$ (P-wave) which will be above S-waves. This is reflected in the fact that the states with positive parity in Table 1 are those with smaller binding energies.

4 The $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$ resonances

Table 2 shows the calculated naive quark-antiquark spectrum in the region of interest of the LHCb for the $J^{PC} = 0^{++}$ and 1^{++} channels. A tentative assignment of the theoretical states with the experimentally observed mesons at the LHCb experiment is also given. It can be seen that the naive quark model is able to reproduce all the new LHCb resonances except the $X(4140)$. The $X(4274)$, $X(4500)$ and $X(4700)$ appear as conventional charmonium states with quantum numbers 3^3P_1 , 4^3P_0 and 5^3P_0 , respectively. A complete study of the decay widths of these states has been performed in Ref. [11] showing that the total decay width of the $X(4274)$, $X(4500)$ and $X(4700)$ are, withing errors, in reasonable agreement with the data.

To gain some insight into the nature of the $X(4140)$, that does not appear as a quark-antiquark state, and to see how the coupling with the open-flavour thresholds can modify the properties of the naive quark-antiquark states predicted above, we have performed a coupled-channel calculation including the $D^* D_1^{(\prime)}$, $D_s D_s$, $D_s^* D_s^*$ and $J/\psi\phi$ channels for the $J^{PC} = 0^{++}$ sector; and the $D_s D_s^*$, $D_s^* D_s^*$ and $J/\psi\phi$ ones for the $J^{PC} = 1^{++}$ sector. These are the allowed channels whose thresholds are in the region studied by the LHCb.

Our results for the $J^{PC} = 0^{++}$ channel can be found in Ref. [11]. Therein, we conclude first that the net effect of coupling the thresholds to both naive quark-antiquark states is to modify the mass of the bare $c\bar{c}$ states in a modest amount. The second observation is that the total decay widths are significantly reduced.

For the coupled-channel calculation in the $J^{PC} = 1^{++}$ channel, we found only one state with mass 4242.4 MeV and total decay width 25.9 MeV. This state is made by 48.7% of the $3P$ charmonium state and by 43.5% of the $D_s D_s^*$ component. Our theoretical results are given in Tables 3 and 4.

As we do not find any signal for the $X(4140)$, neither bound nor virtual, we analyze the line shape of the $J/\psi\phi$ channel as an attempt to explain the $X(4140)$ as a simple threshold cusp (see again

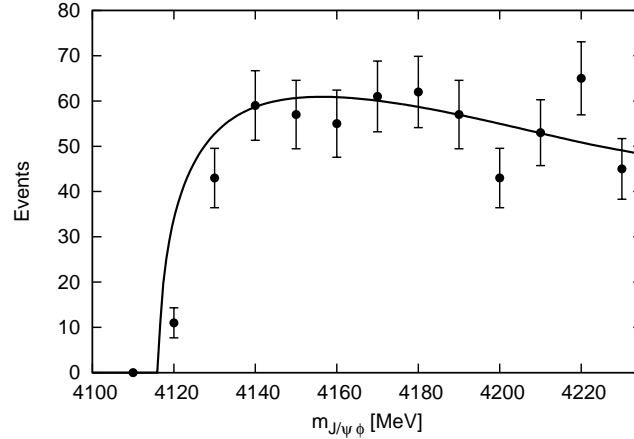


Fig. 1 Line-shape prediction of the $J/\psi\phi$ channel. The curve shows the production of $J/\psi\phi$ pairs via direct generation from a point-like source plus the production via intermediate $c\bar{c}$ states. Note that the production constant has been fitted to the data (see Ref [11] for the details).

Ref. [11] for details). Figure 1 compares our result with that reported by the LHCb Collaboration in the $B^+ \rightarrow J/\psi\phi K^+$ decays. The rapid increase observed in the data near the $J/\psi\phi$ threshold corresponds to a bump in the theoretical result just above such threshold. This cusp is too wide to be produced by a bound or virtual state below the $J/\psi\phi$ threshold.

5 Summary

As a summary, our results confirm the fact that there are several states with a $\bar{D}^{(*)}\Sigma_c^{(*)}$ structure in the vicinity of the masses of the $P_c(4380)^+$ and $P_c(4450)^+$ pentaquarks reported by the LHCb.

Concerning the other resonances, three of them, namely $X(4274)$, $X(4500)$ and $X(4700)$, are consistent with bare quark-antiquark states with quantum numbers $J^{PC} = 1^{++}(3P)$, $J^{PC} = 0^{++}(4P)$ and $J^{PC} = 0^{++}(5P)$, respectively.

In the 1^{++} sector, we do not find any pole in the mass region of the $X(4140)$. However, the scattering amplitude shows a bump just above the $J/\psi\phi$ threshold which reproduces the fast increase of the experimental data. Therefore, the structure showed by this data around 4140 MeV should be interpreted as a cusp due to the presence of the $D_s D_s^*$ threshold.

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